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Beyond the Limits of Single Resonance Huygens' Metasurfaces

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Abstract

Huygens' metasurfaces have enabled high efficiency electromagnetic wavefront manipulation based on sub-wavelength resonant particles. Utilizing co-located single electric and magnetic resonances, they provide perfect transmission in an ultrathin meta-atom configuration. However, by using only single resonances, there is an inherent limitation on the achievable bandwidth and phase coverage which essentially limits the metasurface applications. In this paper, we review these fundamental limitations of Huygens' metasurfaces and show how the bandwidth may be optimized within the constraints of single resonance meta-atoms. We then propose a design methodology to obtain Huygens' metasurfaces with two electric and two magnetic resonances in a single meta-atom configuration, paving the way for further metasurface bandwidth improvement.

1 Introduction

In metasurfaces, co-locating electric and magnetic dipole moments within a single meta-atom configuration has been a key recipe for obtaining high transmission operation while providing wide-space of phase coverage. The so-called Huygens' surface has been proposed and realized quite recently in the microwave spectrum [1], while the concept of combining orthogonal electric and magnetic dipole moments goes beyond the topic of metasurface itself with the work of Kerker in 1983 [2]. Despite the promise of Huygens metasurfaces to realize maximum transmission and suppress reflection, the use of resonant modes in their meta-atoms fundamentally limits the bandwidth of operation. This is in contrast with recent efforts to obtain broadband achromatic metasurfaces, in which optical performance of the metasurface - such as focal length or angle of refraction, are kept identical, demanding large bandwidth meta-atoms [3, 4]. Due to the limitation of bandwidth in Huygens' metasurfaces, most of the achromatic metasurfaces reported so far have used either thick wave-guiding structures [5] or Pancharatnam Berry phase [6], and very few works are based on Huygens' meta-atoms.

In controlling electric and magnetic dipolar responses, Huygens' metasurfaces can be realized in three metallic layer configuration. Using this method, the impinging waves undergo retardation between the outer metallic layers resulting in magnetic dipole moments, while interaction of the wave with inner metallic layer produces electric dipole moments. This method suits well the application in lower frequencies, where printed circuit fabrication can be used in meta-atom implementation. The method is also convenient since the requirements of the three metallic layers can be analytically obtained, with transmission line model of dielectric materials and equivalent impedances of the patterned metallic layers. In a series of studies, we used this meta-atom modeling to derive bandwidth limitation of achromatic and dispersive metasurfaces. Based on the argument that the impedances should be passive and causal, we showed that achromatic metasurfaces have trade-offs between bandwidth and the aperture size [7]. Moreover, utilizing the time-bandwidth product of single resonance meta-atoms, we revealed the influence of substrate electrical thickness in these metal-dielectric-metal meta-atom configuration [8]. The larger the dielectric thickness the better bandwidth improvement can be achieved, however, the bandwidth starts to degrade when the thickness goes beyond quarter of the operating wavelength. This findings show that based on single resonance Huygens' meta-atoms, it is possible to optimize the bandwidth by increasing the substrate electrical thickness approaching the quarter wavelength-limit.

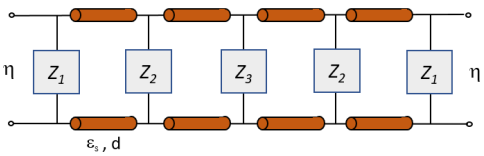

Figure 1. Broadband Huygens' meta-atom based on five metallic patterned layers modeled as five cascaded impedances.

Despite the efforts to optimize the bandwidth within single resonance meta-atoms, the limitation of phase coverage means achromatic Huygens' metasurfaces may have only small numerical aperture. Broadening the bandwidth and aiming for large numerical aperture of metasurfaces is crucially important at microwave and millimeter-wave frequencies, having significance in various applications including wireless communication, sensing and power transfer. Therefore in this paper we propose a Huygens' meta-

surface that exceeds the single resonance limitations by carefully engineering two electric and two magnetic resonances in a single meta-atom configuration. The implementation involves five layers of metallic patterned structure supported by four dielectric substrates as illustrated in Figure 1. We show that in a single meta-atom, a higher than -3dB transmission can be achieved with a wide phase coverage of almost 4π. Utilizing this meta-atom configuration, we design an achromatic metasurface lens that maintain the same focal-length over 43% normalized bandwidth and evaluate the performance via a point dipole model.

2 Huygens' Metasurfaces with Multiple Resonances

Before discussing multiple resonance Huygens' metasurfaces, it is important to take note on basic bandwidth optimization method on single resonance meta-atoms. As we derived in [8], the normalized bandwidth of dispersive metasurfaces based on single resonance meta-atoms can be written as,

$$\frac{\Delta\omega}{\omega_{\min}} \leq \frac{Z_s \sin^2(\omega_{min} t_s)}{Z_o \omega_{\min} t_s} \tag{1}$$

Here, $\Delta\omega$ is the bandwidth, ω_{min} is the minimum operating frequency, $Z_s = \eta/\varepsilon_s$ is the substrate impedance, where η is wave impedance and ε_s is the substrate permittivity, and $Z_o = \eta/\cos\theta_o$ is the impedance of the reflected wave. Propagation through the substrate is expressed as a time delay $t_s = \sqrt{\varepsilon_s} d/c$ where d is substrate dielectric thickness and c is the speed of light in vacuum. A certain diffractive angle θ_o is considered, in which for $\theta_o = 0$ implies that the metasurface is homogeneous without any prescribed diffraction angle ($Z_o = \eta$). Although reflective operation was considered in the derivation, the bandwidth limit is also relevant for transmissive meta-atoms, since the mechanism of obtaining single resonances does not significantly change. In the case of reflective metasurface, the magnetic resonance appears due to mirror current in the ground planes, while in the transmissive three layer Huygens' metasurface, the magnetic resonance appears due to the retardation of the waves with the presence of two identical outer layers.

From this bandwidth limit we can see that substrate parameters very much influence the extent of the realizable bandwidth. As shown in Figure 2 the largest normalized bandwidth is obtained when the thickness is approaching a quarter of the wavelength, and when the permittivity is low. This quarter wavelength thickness which gives approximately largest bandwidth is written as $d_{peak} = \lambda_{min}/4\sqrt{\varepsilon_s}$ and is plotted as a dashed line in Figure 2. Based on this bandwidth limit, choosing larger electrical thickness is favorable for bandwidth improvement. In Figure 2, we plot the normalized bandwidth of a metasurface having substrate of

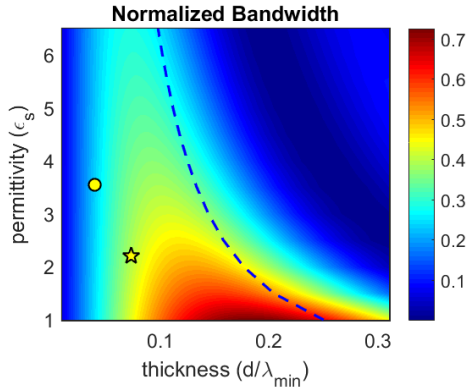

Figure 2. Normalized bandwidth with respect to dielectric substrate parameters obtained from the bandwidth limit in Eq. (1). Dashed line indicates the quarter wavelength thickness in each permittivity value. Circle label indicates the substrate parameters used in Ref [9] with $\varepsilon_s = 3.55$ and thickness of $d = 1.52$ mm. Star label indicates the substrate parameters used here with $\varepsilon_s = 2.2$ and $d = 1.575$ mm.

Roger 4003C (similar to Ref [9]) with $\varepsilon_s = 3.55$ and thickness of $d = 1.52$ mm as indicated by a circle label. Here, in order to optimize the bandwidth, we use Roger RT/duroid 5880 substrate with lower dielectric constant ε_s =2.2 and a slightly larger substrate thickness $d = 1.575$ mm as indicated by a star label in Figure 2. By changing this substrate parameters, there is improvement of realizable bandwidth from 23% to 38%. Note that this bandwidth is for a homogeneous metasurface, without prescribing any diffractive angle or considering achromatic operation.

After investigating the possibility to obtain bandwidth improvement by adjusting the substrate parameters, we now want to know the possibility of obtaining broader bandwidth by adding resonances. It should be mentioned here that the method of engineering multiple resonances has been used since early works on diffractive structures and reflect-arrays to enhance the operational bandwidth [10]. In transmissive operation, multiple resonance metasurfaces have been realized based on filter synthesis theory [11]. However, despite the reported metasurface achieved achromatic operation, the phase coverage is less than 2π and a complicated numerical optimization is required in the design. Here, we revise some of the derivation used in [11] for the required impedance in each layer, in order to obtain larger bandwidth with smaller number of metallic layers. We incorporate the optimized substrate parameters as discussed in the previous paragraph and use it consistently for all meta-atoms, in contrast to [11] that uses varying thickness for different meta-atoms. Instead of using capacitive or inductive impedances in each layer as in [11], we use an LC-pair with controllable equivalent impedance. Five layer impedances are arranged within one meta-atom, with a symmetrical configuration of three distinct parameters, i.e. Z_1, Z_2, and Z_3, as shown in Figure 1. The resulting meta-atom is similar to a fifth-order Butterworth bandpass-

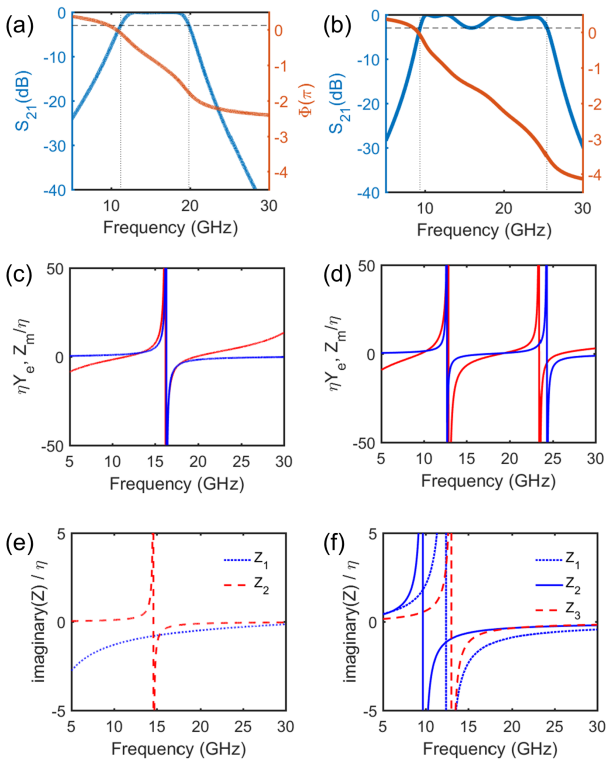

Figure 3. Transmission amplitude and phase spectra from (a) three layers Huygens' meta-atom, (b) five layers Huygens' meta-atom. Normalized electric admittance (red lines) and magnetic impedance (blue lines) from (c) three layers Huygens' meta-atom, (d) five layers Huygens' meta-atom. The corresponding impedances of each layer from (e) three layers Huygens' meta-atom, (f) five layers Huygens' meta-atom.

filter used in Ref [11] however with much reduced number of layers (using the method in [11] nine layers are required).

In order to evaluate the electric and magnetic resonance within the meta-atom, we compare the proposed five metallic layers meta-atom with the three metallic layers Huygens' meta-atom in Figure 3(c)-(d). We can confirm that the proposed meta-atom has two electric and two magnetic resonances within the operational bandwidth, while using the three layers meta-atom approach only single electric and single magnetic resonances exist within the operating bandwidth. The transmission amplitude and phase spectra are plotted in Figure 3(a)-(b) where the dashed lines indicates -3dB transmission and dotted lines indicates the -3dB bandwidth. It can be seen that the phase coverage where the amplitude maintains minimum -3dB bandwidth is approximately 2π in the single resonance case, while for the multiple resonance case, the phase coverage is almost 4π. For the single resonance Huygens' meta-atom, the corresponding impedances of each layer with two distinct parameters Z_1 and Z_2 are plotted in (e), while for multiple resonance five layers Huygens' meta-atom with three distinct parameters Z_1, Z_2 and Z_3, they are plotted in (f).

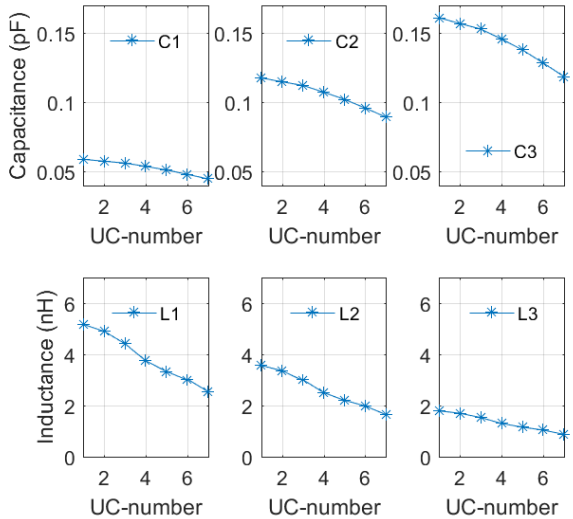

Figure 4. The required LC-pairs of each metallic patterned layer for the achromatic Huygens' metasurface lens with multiple resonance.

Based on this five layers meta-atom structure, we design an achromatic metasurface lens at the center frequency of 17 GHz ($\lambda = 17.6$ mm). The aperture size of the metasurface lens is D=84 mm (5λ), discretized into 14 meta-atoms each having a width of 6 mm. The phase focal length of the metasurface lens is F=84 mm, therefore the lens has F/D=1 or numerical aperture of NA=0.35. The required LC-pairs for each metallic layer are plotted in Figure 4 where we can see that the capacitance increases for the metallic layers located in the middle of the meta-atom (Z_2 and Z_3), while for the inductance, outer layers (Z_1) have the largest variation. These LC pairs could be realized as metallic dog-bones or other structures with enough degrees of freedom to control both inductance and capacitance values. To evaluate the performance of the proposed achromatic metasurface, we use a point dipole model as explained in [12]. Considering the metasurface as a one dimensional array of dipoles arranged along the x-axis, the field scattered by the metasurface can be formulated as

$$E_y(x,z) = \sum_{x,z} \frac{A(x_m,\omega)}{\sqrt{r}} e^{-j(k_0 r + \Phi(x_m,\omega))}. \qquad (2)$$

Here, A is the meta-atom amplitude response and Φ is the phase response which depend on frequency ω and on location x_m (distance of the meta-atom relative to the center of the metasurface), r is the distance from the meta-atom location to arbitrary point x,z within the xz-plane in front of the metasurface and $k_0 = 2\pi/\lambda$ is the wave number. We see from Figure 5 that the metasurface can maintain the same focal length over 6 GHz bandwidth, which is equivalent to normalized bandwidth of $\Delta\omega/\omega_{min} = 43\%$. This bandwidth is larger than using only single resonance Huygens' meta-atom, where the maximum realizable bandwidth of the same achromatic lens is only 20%, according to the limit derived in Ref [8].

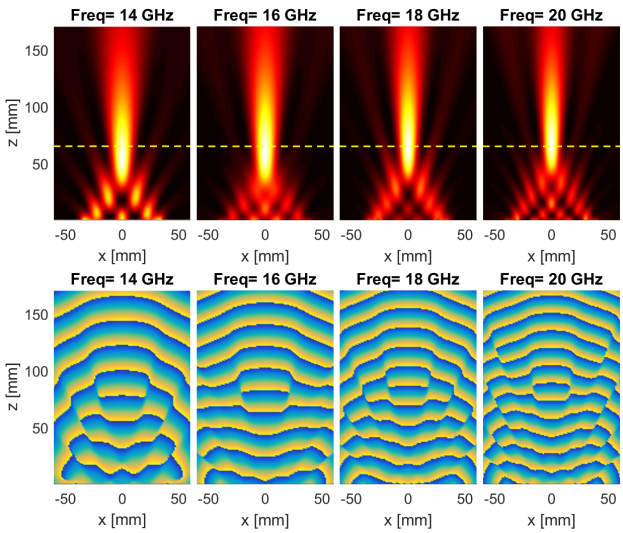

Figure 5. Normalized scattered field obtained analytically using point source model for broadband achromatic metasurface lens using two resonance meta-atoms. Top figures are for the amplitude profile and bottom figures are for the phase profile.

3 Conclusion and Outlook

In conclusion, it is possible to design broadband Huygens' metasurfaces based on engineering two co-located electric and magnetic resonances within a single meta-atom. Using printed circuit method, five metallic patterned layers supported by four dielectric substrates can be used as an implementation medium. The thickness of each dielectric substrate can be consistently made same and optimized for highest possible bandwidth. Each metallic patterned layer is represented by an LC-pair, where the required value for a particular metasurface design can be analytically obtained. In this reported work, a broadband achromatic metasurface lens was designed based on the proposed meta-atom structure achieving 43% normalized bandwidth as evaluated by the point dipole model. Since the metasurfaces realized in this work is only based on analytical calculation, the next task is to design each metallic patterned layer to realize the designed achromatic operation. Further to the work reported here, it is also interesting to see how the proposed meta-atom can be used to obtain metasurface lenses with controllable focal length dispersion.

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